

Coronal activity among open cluster stars

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Abstract. Focusing on *ROSAT* results for clusters in the $\sim 20 - 600$ Myr range, I first summarize our current understanding of the X-ray activity – rotation – age relationship. Then, the problem of the Hyades K and M dwarfs binaries is addressed: *1.* most K and M-type binaries in wide systems are X-ray brighter than single stars; *2.* binaries seem to fit into the same activity – rotation relationship as single stars. Points *1.* and *2.* suggest that the distributions of rotations of single and binary stars should also show a dichotomy, but the few available rotational data do not support the existence of such a dichotomy. Rotational periods for a larger sample of binary and single stars should be acquired before any conclusion is drawn. Finally, I discuss the topic whether the activity–age dependence is unique, as commonly thought. Whereas the comparison of Praesepe to the Hyades might imply that this is not the case, the X-ray activity of a sample of Hyades-aged field stars instead supports the common thinking.

1. Introduction

As an introductory remark, it is useful to recall that X-ray emission from solar-type and lower mass stars is thought to originate from a hot corona heated and confined by magnetic fields that are generated through a dynamo process. It is therefore expected on theoretical grounds that the level of X-ray emission, or coronal activity, should depend on at least the properties of the convective zone, on stellar rotation and, through the rotation–age dependence, on stellar age. X-ray surveys of stellar clusters offer a powerful tool to empirically prove and quantitatively constrain the dependence of coronal activity on these parameters and, possibly, on additional ones, thus providing feedback to the theory. *ROSAT* PSPC and HRI observations have provided X-ray images for about 30 open clusters in the age range between $\sim 20 - 600$ Myr (see Table 1 in Jeffries 1999, for the most updated list). Our understanding of coronal properties of solar-type and low mass stars in clusters is now considerably deeper than a decade ago, but, at the same time, new puzzles have been raised by *ROSAT* results.

The main results and questions emerged from *ROSAT* observations of clusters have been discussed in several reviews in the last few years. The age – rotation – activity paradigm (or ARAP) has been discussed at length by Caillault (1996), Randich (1997), and Jeffries (1999). Other issues, such as time variability (Caillault 1996; Stern 1999; Jeffries 1999), insights from spectra (Caillault

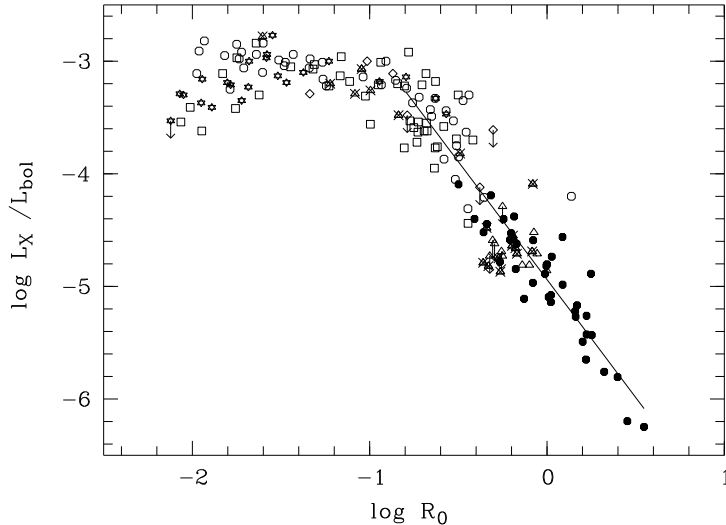


Figure 1. $\log L_X/L_{\text{bol}}$ vs. the logarithm of the Rossby number for cluster and field stars. Open symbols are as follows; circles: Pleiades; squares: IC 2602 and IC 2391; stars: Alpha Persei; triangles: Hyades single stars; crossed triangles: Hyades binaries; diamonds: IC 4665. Filled symbols: field stars. The line represents the regression fit of the points with $\log R_0 > -0.8$.

1996), supersaturation (Randich 1998), and observational limits and analysis techniques (Micela 1996) were also addressed. I refer to those papers for a detailed discussion of the above topics. In the present paper I will first present a summary of the general picture of the ARAP that we gathered from *ROSAT* data; second, I will address an issue that was only marginally discussed in previous reviews, namely binaries and their influence on cluster X-ray luminosity distribution functions (XLDF). Finally, I will focus on the exceptions to the ARAP and on the controversial question whether the X-ray properties of a cluster at a given age can be considered as representative of all clusters at that age. Within this context, I will compare cluster stars with field stars.

The following sources of X-ray data were used; *Pleiades*: Stauffer et al. (1994), Micela et al. (1996), Micela et al. (1999a); *IC 2602*: Randich et al. (1995); *IC 2391*: Patten & Simon (1996); *Alpha Persei*: Prosser et al. (1996); *Hyades*: Stern et al. (1995), Pye et al. 1994; *IC 4665*: Giampapa et al. (1998); *NGC 2547*: Jeffries & Tolley (1998); *NGC 2516*: Jeffries et al. (1997); *Blanco 1*: Micela et al. (1999b); *NGC 6475*: Prosser et al. (1995), James & Jeffries (1997); *Coma Berenices*: Randich et al. (1996b); *Praesepe*: Randich & Schmitt (1995).

2. A consistent picture: the ARAP

The main results evidenced by *ROSAT* observations of open clusters can be summarized as follows:

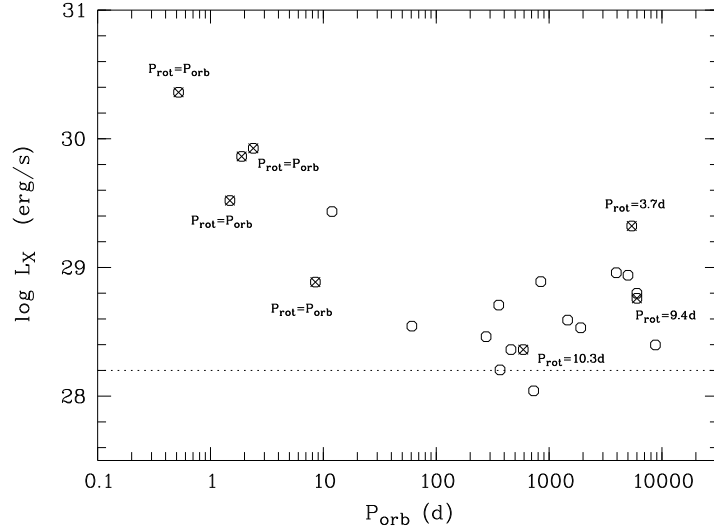


Figure 2. $\log L_X$ vs. orbital period for Hyades binaries with $B-V \geq 0.8$. Crossed circles denote stars with available measurements of rotational periods. The horizontal line represents the median L_X of single K dwarfs.

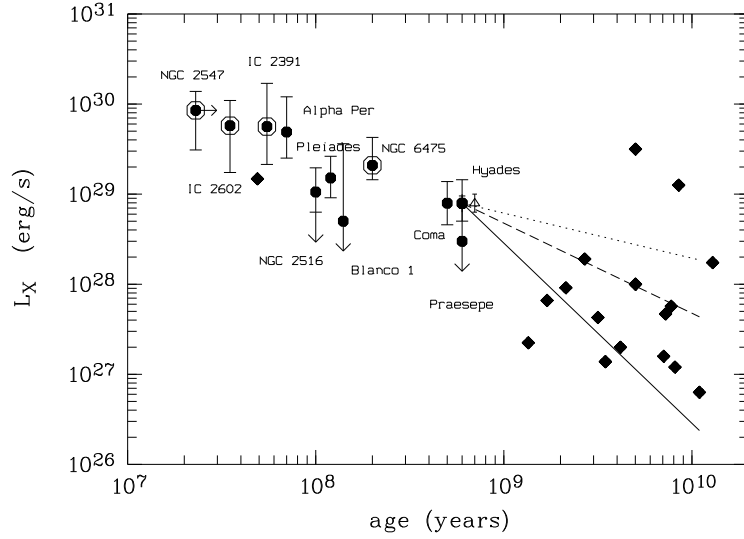


Figure 3. X-ray luminosity as a function of age for solar-type stars in clusters (circles) and in the field (diamonds). For the clusters the median L_X is plotted. The open triangle represents the median of a sample of Hyades-aged field stars. The vertical lines connect the median with the 25th and 75th percentiles. Circled symbols denote X-ray selected cluster samples. The three lines represent power laws with indices α equal to -0.5 (dotted), -1 (dashed), and -2 (solid).

- If we exclude “outliers” or exceptions which I will discuss in Sect. 4, the average level of X-ray activity decays with age. Whereas this was already well established from *Einstein* observations of the Hyades and the Pleiades (e.g., Micela et al. 1990), the larger number of clusters observed by *ROSAT* and the finer age sampling have allowed deriving a more detailed activity vs. age relationship. The decay timescales appear to be different for different masses (the lower the mass the longer the timescale) and the L_X vs. age functional dependence is not simply described by the Skumanich power law (Skumanich 1972);
- In all clusters the maximum X-ray luminosity (L_X) decreases towards later spectral-types; at a given spectral-type, a significant scatter in L_X is observed; as a consequence, whereas the median L_X decreases with age, the XLDFs for clusters of different ages are not “parallel” one to another and some overlap is present. This means that X-ray activity cannot be unambiguously used as an age diagnostic;
- The X-ray activity level does depend on rotation only up to a rotation threshold above which X-ray emission saturates; for stars rotating faster than this threshold the ratio of the X-ray luminosity over bolometric luminosity, L_X/L_{bol} , is about constant and equal to 10^{-3} . Note that a definitive explanation for saturation has not yet been offered.

ROSAT observations of clusters are complemented by determinations of rotational velocities and/or periods in a variety of clusters. Very briefly, it is now well established that stars arrive on the Zero Age Main Sequence (ZAMS) with a large spread in their rotation rates and then they slow down with mass-dependent timescales (e.g., Barnes 1999; Bouvier 1997 and references therein).

The use of the so-called Rossby diagram allows incorporating the above points into a unique picture. Noyes et al. (1984) were the first to show that the use of the Rossby number (R_0), the ratio of the rotational period P over the convective turnover time τ_c , which somehow allows formalizing the dependence of activity on the properties of the convection zone, improved the rotation–chromospheric activity relationship for field stars. Randich et al. (1996a) and Patten & Simon (1996) showed this to hold also for the X-ray activity of cluster stars. Taking advantage of the new available periods for several clusters, I produced an updated version of the diagram which I show in Figure 1. X-ray data for field stars were taken from Schmitt (1997) and Hünsch et al. (1998, 1999); periods were taken from Hempelmann et al. (1996); I retrieved periods for most of the clusters from the Open Cluster Database ¹, complementing the ones for the Pleiades with the new measurements of Krishnamurthi et al. (1998) and adding periods for IC 2602 from Barnes et al. (1999). I derived Rossby numbers using the semi-empirical formulation for τ_c given by Noyes et al. (1984). I refer to the paper of Pizzolato et al. (1999) for a discussion of how different ways of estimating τ_c may affect the $\log L_X/L_{bol}$ vs. $\log R_0$ relationship.

¹Open Cluster Database, as provided by C.F. Prosser (deceased) and J.R. Stauffer, and which currently may be accessed at <http://cfa-ftp.harvard.edu/~stauffer/>, or by anonymous ftp to <cfa-ftp.harvard.edu>, cd /pub/stauffer/clusters.

Various features can be noted in the diagram: first, saturation of X-ray activity is evident: it occurs at $\log R_0 \sim -0.8$. The points with a lower Rossby number cluster around $\log L_X/L_{\text{bol}} = -3$ (but note the supersaturation at very low $\log R_0$ –see Randich 1998). Since the diagram includes stars from F down to M spectral-type, the uniformity of the threshold Rossby number below which X-ray emission is saturated, implies that the rotation threshold depends on mass. In other words, if $\log(R_0)_{\text{thr}} = (\log P/\tau_c)_{\text{thr}} = \text{const} \sim -0.8$, then, $P_{\text{thr}} \propto \tau_c$; since τ_c increases with decreasing mass (the convective envelope becomes deeper), the lower the mass, the longer is the threshold period (e.g., Stauffer et al. 1997a). Second, all cluster and field stars fit into a unique relationship. This on one hand means that field and cluster stars behave in a similar way as far as the rotation – convection – activity relation is concerned; whereas this is qualitatively expected –why should field and cluster stars behave differently?– it is good to empirically confirm the expectations. On the other hand, the fact that stars in all clusters lie on the same curve, irrespective of age and mass, implies that the activity–age dependence is most likely an activity–[rotation–convection]–age dependence. Incidentally, whereas a certain amount of scatter around the relation is present, as well as a few outliers, I believe, in agreement with Jeffries (1999), that most of the scatter is likely due to errors and non-uniformity in L_X measurements and to some variability in X-ray luminosities. Third, the linear regression curve has a slope equal to $-2.1(\pm 0.09)$ which, at a given spectral-type (i.e, roughly constant τ_c and stellar radius) is the same functional L_X vs. rotational velocity dependence found by Pallavicini et al. (1981) for field stars.

In summary, the Rossby diagram can be looked at as an evolutionary diagram. Stars arrive on the ZAMS characterized by a range of rotation rates; therefore they occupy different regions of the Rossby diagram, with a significant part of them lying on the saturated part. The maximum luminosity at a given spectral-type is bounded by the saturation condition which explains why it decreases towards late spectral-types; non-saturated stars cause the spread in L_X , whilst saturated stars, in principle, do not contribute to it. As the clusters age, the stars spin-down and they move towards the right of the Rossby diagram. Their L_X remain virtually unchanged until they de-saturate and, once they do not lie anymore on the saturation plateau, they become progressively less active as they continue to spin-down. The fraction of saturated stars in a cluster decreases until, as is the case for the Hyades solar-type stars, all the stars are non-saturated. As a consequence, the mean and median luminosities decay. Since, as we consider later spectral-types, both the spin-down timescales and the saturation threshold period are longer, K and M dwarfs move towards the right of the diagram at a slower rate than solar-type stars (in other words, they remain saturated longer); accordingly, the timescales for the decay of X-ray activity of K and M dwarfs are also longer than for solar-type stars.

3. Binaries

How do binary stars fit into the scenario outlined in the previous section? In principle, there should be no difference between single stars and wide binaries, which, therefore, should follow a “normal” X-ray activity – rotation – age evo-

lution. On the contrary, as well known, binaries in close, tidally locked systems, are rapid rotators even at rather old ages and therefore are expected to show high levels of X-ray activity and to contribute to the high luminosity tail of a cluster XLDF.

In young clusters like the Pleiades, virtually no difference is observed between the X-ray activity level of single and binary stars (e.g., Stauffer et al. 1994); this is indeed not surprising since most of the Pleiades single stars are still rapid rotators because of their young age.

The situation is different in the older Hyades: the X-ray brightest stars in the cluster are well known binaries. Most surprisingly, however, not only tidally locked BY Dra binary systems are found to be more active than single stars, but a high level of X-ray emission is also observed among several wide binaries. The influence of binary systems on the XLDFs of the Hyades has been discussed by Pye et al. (1994), Stern et al. (1995), and Stern and Stauffer (1996). All these studies pointed out that the XLDFs of late-A, F, and G-type binaries are very similar to those of single stars. On the contrary, the XLDFs of binary and single K and M dwarfs show a dichotomy, with the bulk of the binary population being considerably more X-ray active than single stars (see Fig. 10 in Stern et al. 1995 and Fig. 2b of Pye et al. 1994). Pye et al. estimated that the probability that binary and single K-type stars XLDFs are drawn from the same parent population is lower than 0.4 %. Since most of the K-type binaries are in wide systems with orbital periods of the order of a year or longer, enforced rotation could not be the reason for the high activity level. Pye et al. also showed that the higher luminosities of binary K dwarfs could not simply be due to the summed luminosities of single components.

The questions then arise *a)* whether the rotation-activity relationship for binaries is similar to that of single stars and, *b)* if this is the case, why do binaries in long period systems maintain high rotation and activity. Hyades binaries with known rotational periods are plotted as crossed triangles in the Rossby diagram shown in Fig. 1; they clearly follow the same $\log R_0$ vs. L_X/L_{bol} relation as single Hyades stars, with only one binary lying above the locus of the other stars (the star is VB 50, $B-V=0.59$ –i.e., it is not a K/M-type binary). The answer to question *a)* seems therefore to be “yes”.

Figure 2 is a revised version of Fig. 11 of Stern et al. (1995); in the figure I plot the logarithm of X-ray luminosity as a function of the orbital period (P_{orb}) for Hyades binaries with $B-V \geq 0.8$. Orbital periods come from various sources in the literature and were retrieved from the Open Cluster Database. The figure indeed confirms that most wide binaries have a higher L_X than the median luminosity of single stars. Stars with $P_{\text{orb}} \leq 10$ days are synchronous, as expected (e.g., Zahn & Bouchet 1989) and they nicely follow a L_X vs. $P_{\text{orb}} = P_{\text{rot}}$ relationship (in agreement with the trend seen in Fig. 1). The stars with longer orbital periods do not follow such a relationship, but are scattered throughout the diagram. Only three of them have available rotational period, but for these three stars a L_X vs. P_{rot} relationship may also hold, with the most active one being the most rapid rotator. In other words, both Figs. 1 and 2 suggest that rotation is the reason for the high activity level of both short-period and long period binaries and that even binaries in wide systems may maintain a rather high rotation (at least higher than single stars).

As possible explanations for this Pye et al. (1994) and Stern et al. (1995) proposed either the higher initial angular momentum available in binary systems or a different PMS rotational evolution; more specifically, the reasonable hypothesis could be made that binaries disrupt their circumstellar disks earlier than single stars, thus removing a source of rotational braking. If this is the case, as stressed by Stern & Stauffer (1996) the rotational velocity distributions of single and binary K and M dwarfs should also show a dichotomy. Contrarily to this expectation Stauffer et al. (1997b), based on $v \sin i$ measurements, found that the components of SB2 binaries in the Hyades are, on average, slow rotators.

In summary, we are left with the contradicting evidences that **1.** the same L_X vs. period or R_0 relationship holds for binaries and single stars; **2.** wide K and M dwarfs binaries may exist with rather short rotational periods and high activity levels; **3.** the $v \sin i$ distributions of the sample of K and M-type binaries and single stars studied by Stauffer et al. (1997b) do not show any evident dichotomy. I think two possible reasons for this inconsistency can be proposed; first neither the sample of wide binaries with known orbital and rotational periods, nor the sample of Stauffer et al. (1997b) are large enough, and more important, complete. Second, rotational periods of ~ 10 days correspond, for stars with $B-V \sim 0.9$ (see Fig. 2) to velocities of the order of 4 km/s, lower than the $v \sin i = 6$ km/s detection limit of Stauffer et al. (1997b); this suggests that the dichotomy between single and binary K and M dwarfs may show up only among slow rotators. Rotational periods for a large sample of both binary and single stars are clearly required to further investigate this issue.

4. Problems with the ARAP

As discussed in Sect. 2, most of the *ROSAT* results for open clusters can be explained within the ARAP scenario. Whereas the Rossby diagram shown in Fig. 1 evidences no major deviations from the activity-rotation relationship, exceptions to the age-activity relationship have instead been found. I focus here on solar-type stars, but I mention that problems also exist for lower mass stars.

In Figure 3 I plot the median L_X vs. age for G-type stars ($0.59 \leq B-V_0 \leq 0.82$) in various clusters. The vertical bars denote the luminosity range between the 25th and 75th percentiles of the XLDFs. Field stars are also included in the plot. Their age was taken from Ng & Bertelli (1998) or Edvardsson et al. (1993): all but one are older than the Hyades. The open triangle indicates the median luminosity of a sample of nine field stars with an age similar to the Hyades; I selected these stars using lithium measurements from Pasquini et al. (1994), under the plausible assumption that Li in this color range and up to the Hyades age is a reliable age indicator. Three lines denoting power laws with indices $\alpha = -0.5$ (Skumanich law), -1 , -2 are also shown in the diagram.

The figure witnesses the general trend of decreasing X-ray emission with increasing age, the fact that the decay cannot be simply described by a power law, and the overlap between XLDFs of different clusters (i.e., the most active Hyades stars can be as active as stars in the Pleiades). Not all the clusters, however, fit into the mean trend: Praesepe appears to be the most discrepant

cluster in the diagram. It has about the same age as the Hyades and Coma, but as the figure shows, the bulk of its solar-type stars population is considerably X-ray fainter than the other two clusters (Randich & Schmitt 1995). Barrado y Navascués et al. (1998) demonstrated that such a result is not due to the contamination by non-members in the Praesepe sample. In addition, according to Mermilliod (1997), the distributions of rotational velocities in the Hyades and Praesepe are rather similar, although $v \sin i$ or periods are not currently published and thus it is not possible to check on a star-to-star basis whether Praesepe stars follow the same activity – rotation relationship as the stars in other clusters. In any case, this discrepancy casts doubts on the assumption that the X-ray properties of a cluster at a given age can be considered as representative of all clusters at that age. Totten et al. (1999) and Franciosini et al. (1999) analyzed a *ROSAT* HRI image of NGC 6633, a cluster of about the same age as the Hyades and Praesepe: both studies found that NGC 6633 seems to be more Praesepe-like than Hyades-like, supporting the conclusion that the age-activity relation is not unique (but deeper X-ray observations of NGC 6633 are needed to confirm that NGC 6633 is really less active than the Hyades). On the contrary, as Fig. 3 shows, the median X-ray luminosity of a random sample of field stars at ~ 600 Myr exactly matches the Hyades median (and the spread around the median is very small), supporting the opposite conclusion that the Hyades are indeed the standard at 600 Myr. A solution to this puzzle (at least as far as the Hyades/Praesepe dichotomy is concerned) is possibly offered by the results of Holland et al. (1999) who suggest that Praesepe could result from two merged clusters, with the brightest X-ray sources being found almost exclusively in the main cluster.

Other (minor) inconsistencies are visible in Fig. 3; whereas it is understood why all clusters up to Alpha Persei have about the same median luminosity (there is no substantial spin-down up to that age), a tight age-activity relationship does not appear to hold between ~ 100 and 250 Myr. This, again, would imply that the age-activity relationship is not unique and that other parameters (metallicity? e.g., Jeffries et al. 1997) besides rotation and age influence the level of X-ray activity. However, several sources of uncertainty should be removed before such a conclusion can be regarded as definitive. Namely: *i*) the X-ray data used to compute XLDFs and the median luminosities come from different surveys, with different sensitivities and have been analyzed in different ways (I just used the published X-ray luminosities); *ii*) some of the cluster samples are X-ray selected, and thus biased toward X-ray bright stars; *iii*) some of the cluster samples (e.g., Blanco 1) may be contaminated by non-members; *iv*) the clusters shown in the figure are not on the same age scale; whereas ages for the Pleiades, Alpha Persei, and IC 2391 come from the most recent determinations through the lithium boundary method, the ages for the other clusters are the more traditional ones derived through color-magnitude diagram fitting. Note, for example, that the age of NGC 2547 could indeed be larger (see Jeffries et al. 1999).

Finally, the X-ray activity-age relation for stars older than the Hyades is defined by field stars only, which are scattered throughout the diagram. The figure may suggest that the decay between the Hyades and e.g., the Sun is more rapid than $t^{-1/2}$, but, very obviously, X-ray surveys deep enough to reach main sequence solar-type stars in clusters older than the Hyades are needed.

5. Conclusions

ROSAT observations of clusters have increased our confidence in the ARAP, but, at the same time, have led to results that cannot apparently be fully explained by the ARAP. Before the conclusion is drawn that exceptions to the ARAP really exist, additional X-ray and optical observations should be carried out. The need for X-ray surveys of clusters older than the Hyades or of deeper observations of clusters that have already been observed by *ROSAT* is unquestionable. At the same time, X-ray spectra of cluster stars will allow us to infer their coronal properties and follow their evolution with age, or will possibly provide us with a key to the understanding of saturation and supersaturation. I refer to Jeffries (1999) for a detailed list of the issues that the capabilities of XMM and Chandra will allow us to address.

I would like to stress here that complementary optical data (i.e., additional determinations of periods, rotational and radial velocities, deep imaging; etc.) are also needed in order to address in detail these issues and, possibly, find a solution to the puzzles discussed in the previous sections.

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